

Thermal performance evaluation of a conical solar water heater integrated with a thermal storage system



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ABSTRACT

In the present research, a conical solar water heater (CSWH) with an attached thermal storage tank, with or without a vacuum glass absorber, was analyzed under different operating conditions. For maximum solar radiation of the system, the collector was equipped with a dual-axis tracking system and sun sensor, which kept the system oriented towards the sun at every instant during its operation. A forced cooling system circulated fluid to remove the solar heat from the absorber surface. Performance analyses with and without the vacuum glass absorber were conducted at different mass flow rates, inlet temperatures, and solar irradiation values. The influence of the vacuum glass cover and all operational parameters on the collector efficiency, outlet temperature, and thermal stratification were investigated. The efficiency increased with increasing inlet flow rate, and the maximum efficiency was obtained at a critical flow rate of 6 L/min. When the flow rate was increased beyond this critical value, the efficiency began to decrease. The temperature rise of the working fluid with vacuum glass at a high rate of insolation was considerably higher than without a vacuum glass for all flow rates. Use of a high flow rate deteriorated the thermal stratification process in the storage tank, while it increased the efficiency of the conical solar water-heating system. It can be concluded that the CSWH operates more efficiently if the fluid is heated slightly at a critical flow rate.

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1. Introduction

The demand for renewable energy is increasing, due to the rapid growth of industrialization and the excessive use of fossil fuels, which have adverse effects on global climate change. Solar energy is one of the cleanest, most abundant and environmental friendly sources of renewable energy. To obtain maximum thermal energy from incident solar radiation, solar water heaters with different configurations and designs have been used for various applications [1–5]. Researchers are mainly interested in concentrating solar collectors, which have higher concentration ratios than flat-plate collectors. Many cylindrical and circular concentrators have been used and evaluated, and they can be classified as reflective [6,7] or refractive [8,9].

Numerous authors have studied the performance of solar thermal collectors [10–12]. For example, Zhai et al. performed an experimental study of a concentrating solar collector with a linear Fresnel lens [13], seeking to improve the thermal efficiency of the collector compared to the conventional evacuated tube collector system. Kostic and Pavlovic [14] found that using solar radiation reflectors

at an optimal angle increased the thermal efficiency of a thermal collector in December and June. Tao et al. [15] presented numerical and physical models for evaluating the coupled heat transfer performance of a solar dish collector system. They analyzed five different types of solar thermal collector models under steady-state and quasi-dynamic conditions, to verify the test and model limitations [16]. Ihaddadene et al. [17] analyzed the influence of inclination angle and mass flow rate on the thermal efficiency of a solar thermal collector. Kumar and Rosen [18] used a corrugated absorber surface, which exposes a relatively large area to the incident solar radiation, to increase the thermal performance of a solar water heater.

For maximum efficiency of the solar concentrating system, it is essential that the concentrator be precisely shaped, and that heat losses due to high operating temperatures are reduced. Huang et al. [19] presented an analytical analysis of a solar dish concentrator with a spherical receiver, to calculate the intercept factor for optimal performance under typical working conditions. Lifang and Steven presented a new approach for designing and optimizing large parabolic dish mirrors by using finite element analysis and experimental study [20]. Hazami et al. [21] investigated the long-term thermal performance of a domestic solar water-heating system based on an evacuated tube collector under local weather conditions in Tunisia.

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Nomenclature

A_a	absorber area (m ²)	$\dot{m}_t$	flow rate of the thermal fluid (L/min)
k_a	thermal conductivity of the absorber (W/m K)	μ_t	viscosity of the thermal fluid (kg/m s)
T_a	absorber temperature (°C)	c_t	specific heat of the thermal fluid (J/kg °C)
T_t	thermal fluid temperature (°C)	A_t	area of the thermal fluid (m ²)
T_o	air temperature (°C)	M_s	storage capacity of the tank (kg)
I_a	direct solar radiation (W/m ²)	T_s	storage tank temperature (°C)
c_a	specific heat of the absorber pipe (J/kg °C)	U_L	heat loss coefficient (W/m ² °C)
h_w	convection heat transfer coefficient between absorber and air (W/m ² °C)	F_r	heat removal factor
h_i	convection heat transfer coefficient between absorber and thermal fluid (W/m ² °C)	Q_u	useful energy (W)
$h_{r,sky}$	convection heat transfer coefficient between absorber and the surrounding (W/m ² °C)	T_m	mean temperature (°C)
T_{sky}	effective sky temperature (°C)	Greek letter	
d_o	outer diameter of absorber (m)	τ	transmissivity
d_i	inner diameter of absorber (m)	α	absorptivity
T_d	dew point temperature (°C)	γ_r	radiative reflected factor
Nu	Nusselt number	ρ	reflectivity
L	length of absorber (m)	ω	reflector aperture (m)
t	time (s)	σ	Stefan–Boltzman constant (W m ⁻² K ⁻⁴)
x	distance (m)	ϵ_a	emissivity of the absorber
Re	Reynolds number	η_c	efficiency of collector
Pr	Prandtl number	ρ_t	density of thermal fluid (kg/m ³)
		ρ_a	density of absorber (kg/m ³)

In a conical concentrating system, a conical concentrator reflects the incident solar flux onto an absorber mounted at the focal axis. A high concentration ratio can be attained with the conical surface collector patented by Smith [22]. Several research works have described solar concentrating systems for water heating, but few have used a conical concentrator with a dual-axis tracking system. Some studies describe the use of conical concentrators with one-dimensional tracking systems for air heating [23–25]. However, the literature contains no example of using a conical collector with a dual-axis tracking system equipped with a thermal storage tank for water heating.

In this work, a solar thermal collector with an attached conical concentrator, with or without a vacuum glass absorber, was tested under different operating conditions. The effect of the flow rate on thermal stratification in the thermal storage tank attached to the conical collector was investigated. This study also evaluated whether using a double-tube absorber with vacuum glass could decrease heat losses due to convection, and whether it could increase the thermal efficiency of the system.

2. Theoretical and thermodynamics analysis

2.1. Energy balance for the absorber tube [26]

The heat transfer mechanism and energy balance for the absorber in the collector can be expressed as in Eq. (1), assuming: (i) a negligible temperature gradient through the absorber wall, (ii) convective heat exchange between the thermal fluid and the absorber tube, and (iii) uniform temperature within the absorber tube.

$$\rho_a c_a A_a \partial T_a / \partial t = A_a k_a \partial^2 T_a / \partial x^2 + (\tau \alpha \gamma_r) \omega I_a \rho - \pi d_o (h_w (T_a - T_o) + h_{r,sky} (T_a - T_{sky})) - d_i h_i (T_a - T_t) \quad (1)$$

The $(\tau \alpha \gamma_r) \omega I_a \rho$ term describes the performance of the concentrator, where γ_r is defined as the radiative reflected factor of the incident flux on the concentrator surface of the collector. The transmissivity, absorptivity, and reflectivity of the concentrator

are represented by τ , α , and ρ , respectively. The effective sky temperature is defined as in Eq. (2), and the radiative coefficient between the absorber tube and the ambient is defined as in Eq. (3).

$$T_{sky} = (T_o + 273.15) [(T_d + 200) / 250]^{1/4} - 273.15 \quad (2)$$

$$h_{r,sky} = \epsilon_a \sigma (T_a^2 + T_{sky}^2) (T_a + T_{sky}) \quad (3)$$

where h_i is the convection heat transfer coefficient between the working fluid and the absorber tube given by Eq. (4):

$$h_i = \text{Nu } k_a / L \quad (4)$$

The Nusselt number Nu for fully developed turbulent flow and Reynolds number Re for incompressible flow through a tube [27] are calculated by using Eqs. (5) and (6).

$$\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \quad (5)$$

$$\text{Re} = 4 \dot{m}_t / \pi d_i \mu_t \quad (6)$$

where $\dot{m}_t$ and μ_t are the mass flow rate and viscosity of the thermal fluid, respectively.

2.2. Energy balance for the thermal fluid [26]

The absorber tube is assumed to be completely filled with thermal fluid. The energy balance for the thermal fluid can be estimated by Eq. (7):

$$\rho_t c_t A_t \partial T_t / \partial t + \dot{m}_t c_t \partial T_t / \partial x = \pi d_i h_i (T_a - T_t) \quad (7)$$

where ρ_t , c_t , and A_t are the density, specific heat, and area of the working fluid.

2.3. Energy balance for the storage tank [28]

$$M_s c_t (T_s / dt) = \dot{m}_t c_t (T_t - T_s) - U_L A_c (T_s - T_a) \quad (8)$$

where M_s is the storage capacity of the storage tank, U_L is heat loss factor, A_c is the collector area, and T_t and T_s are the temperatures of the thermal fluid and storage tank, respectively.

2.4. Collector efficiency

The efficiency of the collector is defined as the ratio of useful collected heat to the total incident solar flux. The useful energy gain and instantaneous efficiency [24] of the collector can be calculated by Eqs. (9) and (10), respectively.

$$Q_u = A_c F_r [I_a - U_L (T_m - T_a)] \quad (9)$$

$$\eta_c = Q_u / I_a A_c \quad (10)$$

where T_m is the mean temperature of the collector fluid, F_r is the heat removal factor and Q_u is the useful energy gain.

3. Error analysis

Error analysis is very important in terms of determining the accuracy of the measured results. In the present study, uncertainty related to temperature measurement was the main concern because different temperature sensors at the same location depicted different readings. The uncertainty calculation mainly depended on the mean reading errors of the temperature sensors at different locations. The total percentage uncertainty related to the thermal efficiency of the CSWH system was $\pm 2.0\%$ [29,30]. The accuracy of the other equipment was mainly related to instrument sensitivity and measurement error, as explained in Table 1.

4. System description

The experimental setup and a detailed description of the conical solar water heater assembly are provided in Figs. 1 and 2, respectively. The important geometry sizes, materials and characteristics of CSWH system are shown in Table 2. A series of experiments was conducted between May 2013 and August 2013 at Kangwon National University (latitude $36^{\circ}18'N$, longitude $126^{\circ}24'E$, altitude 100 m), South Korea. The collector assembly was a combination of conical concentrator, double-tube copper absorber, vacuum glass cover, dual-axis tracking system with sun sensor, circulating pump, and 200-L thermal storage tank. The novel double-tube copper absorber was placed at the focal axis of the conical solar concentrator. The absorber surface was painted black with collector paint to reduce heat loss due to convection. For accurate calculations of the solar irradiation and the airflow rate through the collector, a pyranometer and anemometer were mounted near the experimental facility. Use of a dual-axis tracking system enabled the conical concentrator to receive uniform incident flux and maximum reflection on the absorber surface.

Incident solar radiation was measured between 11 a.m. and 4 p.m. when maximum conversion efficiency of solar flux was recorded. The collector inlet, outlet, and tank temperatures were measured by using temperature sensors at different locations. Experiments of the collector performance were repeated with and without the vacuum glass absorber tube while changing the flow rate and other operating conditions. To measure the



Fig. 1. Experiment setup.

temperature in the storage tank, three thermocouples were used, which were placed at the top, middle, and bottom of the tank. The data logger recorded readings from the pyranometer, temperature probes, and anemometer every 10 s. Performance analyses of all experiments were carried out in accordance with verified international standard methods [31,32].

5. Results and discussion

To investigate the performance of the conical solar collector, time-based values of solar radiation, wind velocity, and temperature were recorded between 10 a.m. and 4 p.m., as depicted in Fig. 3. As expected, the maximum value of direct radiation was measured at almost 12:45 p.m., and the outlet temperature increased linearly with time. After 2 p.m., the intensity of solar radiation started to decrease with time. In addition, the present system is a closed loop experimental setup, as increase in time the same working fluid is circulated repeatedly through the loop and raised the inlet temperature up to 82% of its starting value at a given time.

Figs. 4 and 5 show the variation of the collector efficiency with respect to the $(T_m - T_a)/I_a$ parameter at flow rates of 2 and 6 L/min, respectively. For both flow rates, the efficiency of the collector was increased by 10–20% when a vacuum glass absorber was used compared to when it was not. At a flow rate of 2 L/min, the maximum efficiencies with and without the vacuum glass absorber were 58% and 48%, respectively, which increased to 72% and 60%, respectively, at 6 L/min. This change in efficiency can be explained as follows. At low flow rates, the heat transfer of the film and the contact time between the inner absorber surface and the water were increased, leading to an increase in water temperature. The higher water temperature compared to the ambient temperature led to increased heat loss from the absorber surface. As a result, the useable energy and collector efficiency were reduced.

The above results are verified by the data in Fig. 6, which displays the variation in efficiency as a function of inlet temperature with and without the vacuum glass absorber. The collector efficiency decreased with increasing inlet temperature regardless of whether vacuum glass was used. Use of vacuum glass on the absorber tube minimized the (mostly due to convective) heat loss. As a result, the energy converted from incident solar flux into thermal output was increased.

Table 1
Total error and instrument range.

Description	Range	Total error
RTD (PT100Ω)	−200–850 °C	±0.1–0.5% °C
Flow meter	10–100 (m ³ /h)	±0.5% at full scale
Sun sensor	400–1200 nM	±0.025 nM
Pyranometer	0–4000 W/m ²	±1.5% (per year)
Data logger (GL800)	−100–1370 °C	±(0.05% of reading + 1 °C)
Anemometer	1–67 m/s	±0.1 m/s
Due to fitting of elements	–	±0.1 °C
Measurement error	–	±0.25 °C

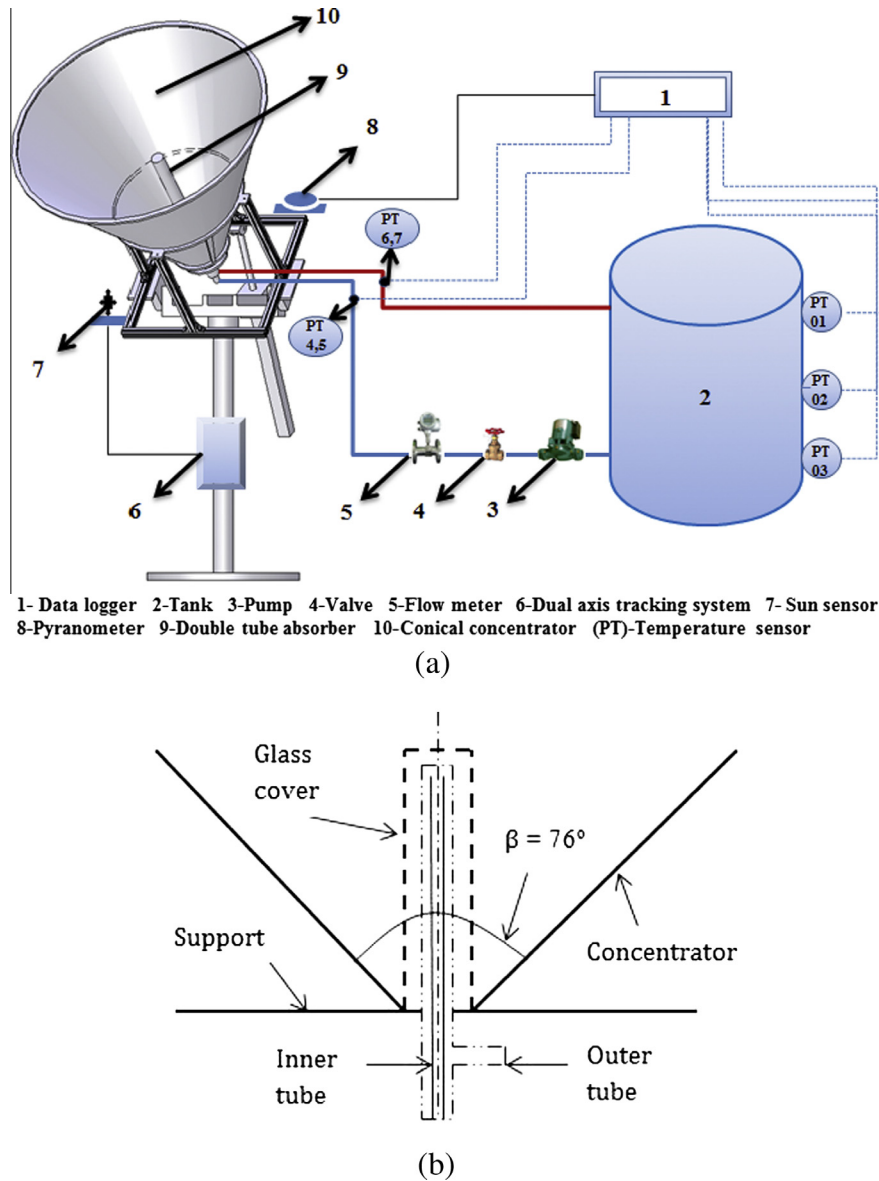


Fig. 2. (a) Detail description of conical collector assembly and (b) schematic view of double tube absorber and concentrator.

Table 2
The characteristics of CSHW system.

Description	Specification
Area of conical concentrator	2.3 m ²
Material of conical concentrator and	18–10 Cr–Ni stainless steel and 1 [23]
γ	
β (koni iç açısı)	76° [24]
Absorber material and thickness	Copper and 2 mm
Absorber inner and outer tubes	16 mm and 29 mm
outer diameters	
Vacuum glass cover	Borosilicate glass tube with anti-reflective coating
	$\tau = 0.965$, $\alpha = 0.012$
Black collector paint	$\alpha = .98$, $\epsilon = 0.88$ [25]
Thermal storage tank	200-L

Figs. 7 and 8 show the water temperature rise with respect to direct radiation for the system with and without a vacuum glass absorber, respectively, at different flow rates. The highest temperature rise of 35 °C was achieved with vacuum glass at a flow rate of 2 L/min. This finding was in accordance with our expectation that

the accumulation of heat on the absorber surface would increase as the intensity of incident solar radiation increased. In addition, the temperature rise of water inside the absorber increased due to a high heat exchange rate between the fluid and absorber. As a result, water heating was prolonged in the presence of the vacuum glass at a low flow rate.

Experimental performance analysis was employed to calculate the critical flow rate that maximized the efficiency of the conical thermal collector. Fig. 9 depicts the variation in collector efficiency and temperature rise as a function of flow rate, with and without the vacuum glass absorber. The efficiency increased and temperature rise decreased with increasing mass flow rate of water. Eventually, a critical flow rate of 6 L/min was reached, such that the efficiency began to decrease with further increases in flow rate beyond the critical value. For example, the maximum efficiency was 66% at 6 L/min, which decreased to 46% at 7 L/min. The pumping and plumbing requirements changed for higher flow rates beyond the critical point, leading to decreased system efficiency. Furthermore, at low flow rates, the temperature rise must be relatively high for the accumulated heat to be removed from the

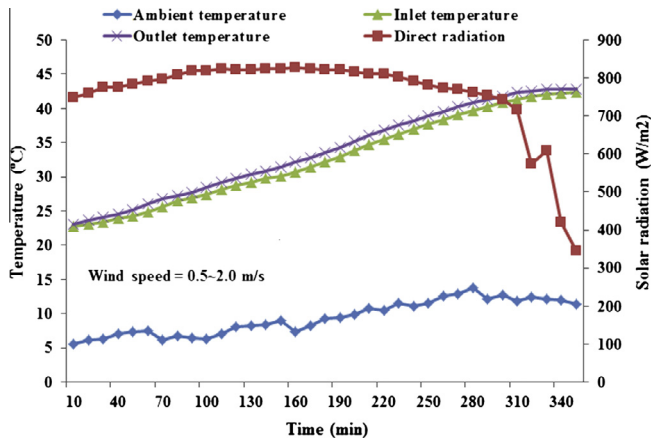


Fig. 3. Daily time based variation of solar radiation, wind speed and temperatures.

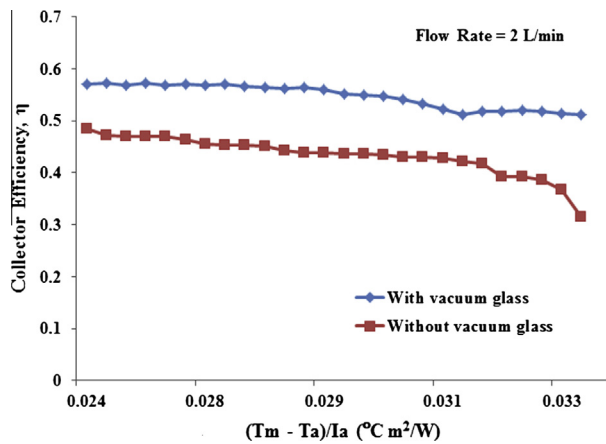


Fig. 4. Change in efficiency against $(T_m - T_a)/I_a$ for flow rate of 2 L/min.

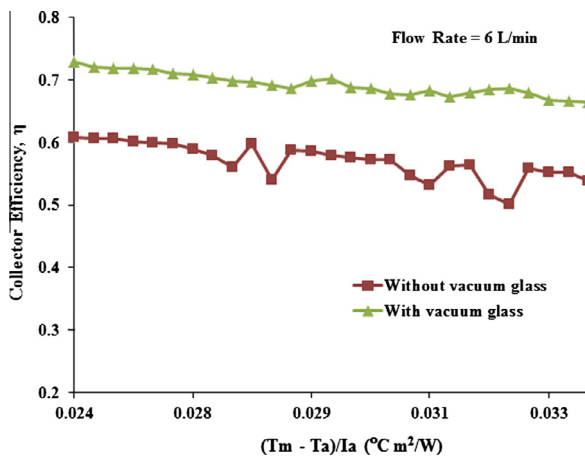


Fig. 5. Change in efficiency against $(T_m - T_a)/I_a$ for flow rate of 6 L/min.

absorber surface. The mean temperature of the absorber surface increased due to increased heat loss from the absorber surface to the ambient environment. However, the values of heat loss were comparatively low when the vacuum glass absorber was used. At high flow rates, the value of the temperature rise was low, which was ideal for high efficiency.

Table 3 presents the values of the convection heat transfer coefficient between the absorber tube and water with vacuum glass at

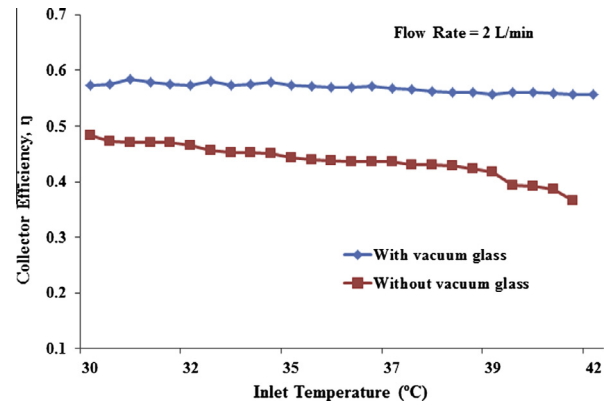


Fig. 6. Variation of collector efficiency in function of inlet temperature.

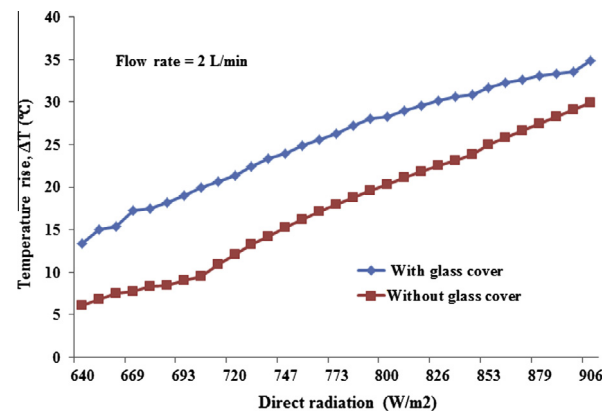


Fig. 7. Variation of temperature rise with respect to direct radiation for 2 L/min.

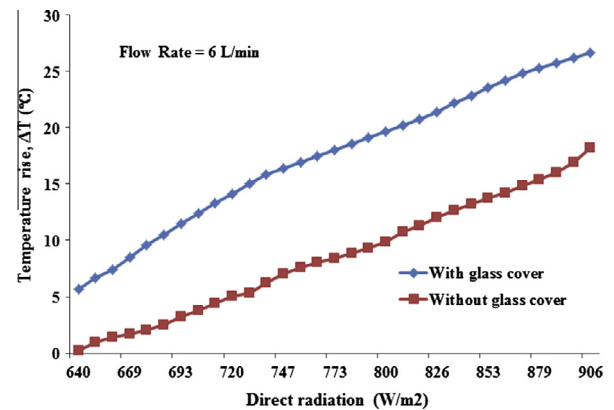


Fig. 8. Variation of temperature rise with respect to direct radiation for 6 L/min.

different flow rates. The highest convection heat transfer coefficient was $56.4 \text{ W/m}^2 \text{ } ^\circ\text{C}$, which was obtained at the critical flow rate of 6 L/min with a vacuum glass absorber.

The influence of the flow rate of fluid exiting the collector on the thermal stratification process in the tank attached to the system was investigated. Thermal stratification is not useful for a solar collector thermal storage system because it reduces the system performance. To simulate deterioration of the thermally stratified fluid layers inside the storage tank, a parametric analysis was performed by varying the mass flow rate of the working fluid. Figs. 10 and 11 show the variation of temperature along the tank length as a function of time for flow rates of 2 and 6 L/min. At the lower flow

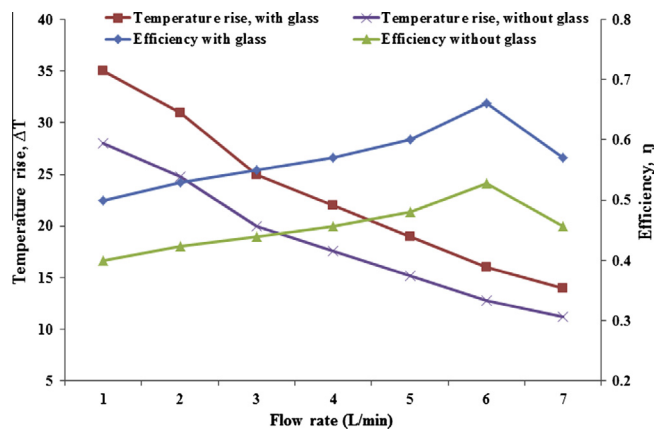


Fig. 9. Changes in temperature rise and efficiency against flow rate with and without vacuum glass.

Table 3

Convection heat transfer coefficient between absorber tube and fluid.

Flow rate (L/min)	Convection heat transfer coefficient ($\text{W/m}^2 \text{ } ^\circ\text{C}$)	Efficiency (%)
2	28.4	42
5	46.6	59
6	56.4	69
7	42.79	53

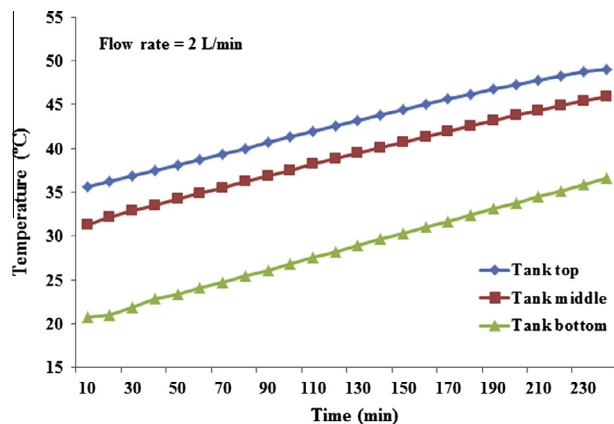


Fig. 10. Variation of tank temperature at different position in function of time at 2 L/min.

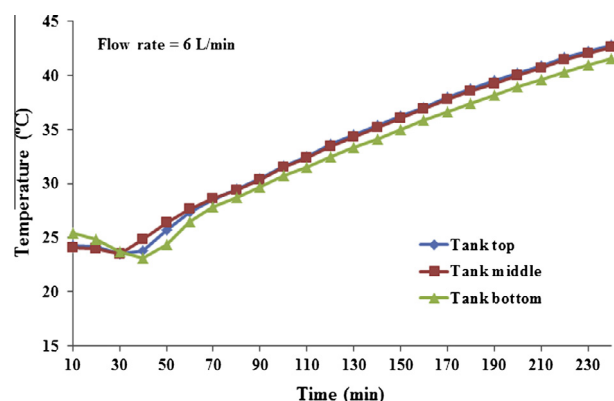


Fig. 11. Variation of tank temperature at different position in function of time at 6 L/min.

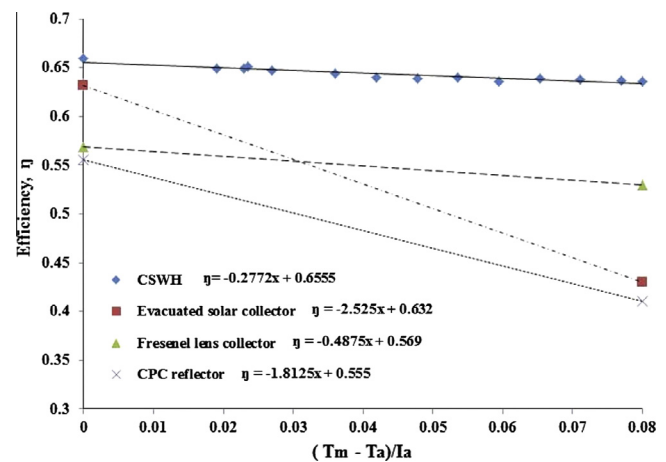


Fig. 12. Performance comparison of CSWH system with different solar collectors.

rate, a high temperature difference between two consecutive layers of fluid was observed, which increased the thermal stratification. In contrast, at 6 L/min, mixing was increased between the stratified layers in the storage tank, which reduced the thermal stratification process. In addition, the temperature difference decreased from top to bottom in the tank at the higher flow rate, which improved the system efficiency.

In order to analyze the reliability of CSWH system, the efficiency of the proposed system is compared with the efficiency of different solar collectors [33,13,34]. Fig. 12 illustrates the performance of system in term of y-intercept as heat removal factor and slope as thermal loss of best fit line, respectively. It is observed that the efficiency of CSWH is a bit higher than the other solar concentrating systems, but slope value is in accordance well with a Fresnel lens solar collector [13]. This can be explained as the thermal losses decrease in concentrating system and high thermal efficiency can be achieved even under higher temperature range. Compared it to reference [34], the optical efficiency is close to CSWH with little difference of 3%, but the slope or thermal losses of evacuated tube collector are much higher than all above systems. It is concluded that the present system had a higher efficiency as compared with previous published results, the reason is the whole angular surface of the absorber is directly exposed to concentrated solar radiation. In summation, the attached dual axis tracker and sun sensor enables this system to absorb maximum solar radiation all day long.

6. Conclusion

In this work, a solar water heating system with a conical concentrator employing a double-tube absorber with and without vacuum glass was evaluated under different operating conditions. The efficiency of the absorber with vacuum glass was 20% higher than the absorber without glass for all flow rates. When the inlet temperature and solar radiation of the system were increased, the temperature rise was increased for all flow rates, although the outcome was most prominent at a low flow rate of 2 L/min when the vacuum glass absorber was used. The collector efficiency increased linearly with increasing flow rate, and the highest value was obtained at a critical flow rate of 6 L/min. Above this critical point, further increases in flow rate led to a decrease in efficiency because the pumping and plumbing requirements of the system were changed. These findings also show that the use of a high flow rate in a conical solar thermal collector reduces the phenomenon of thermal stratification in the storage tank and enhances the system efficiency. Further research is ongoing for comparing the numerical

and experimental results and taking into account the optimal design of CSWH system under different operating conditions.

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References

- [1] Ziapour Behrooz M, Aghamiri Azad. Simulation of an enhanced integrated collector – storage solar water heater. *Energy Convers Manage* 2014;78: 193–203.
- [2] Taheri Y, Ziapour Behrooz M, Alimardani K. Study of an efficient compact solar water heater. *Energy Convers Manage* 2013;70:187–93.
- [3] Kostić Ljiljana T, Pavlovic Zoran T. Optimal position of flat plate reflectors of solar thermal collector. *Energy Buildings* 2012;45:161–8.
- [4] Cruz Jose MS, Hammond Geoffrey P, Reis Albino JPS. Thermal performance of a trapezoidal-shaped solar collector/energy store. *Appl Energy* 2002;73: 195–212.
- [5] Kumaresan Govindaraj, Sridhar Rahulram, Velraj Ramalingom. Performance studies of a solar parabolic trough collector with a thermal energy storage system. *Energy* 2012;47:395–402.
- [6] Kongtragool Bancha, Wongwises Somchai. Optimum absorber temperature of a once- reflecting full conical concentrator of a low temperature differential Stirling engine. *Renewable Energy* 2005;30:1671–87.
- [7] Tao Taao, Hongfei Zheng, Kaiyan He, Mayere Abdulkarim. A new trough solar concentrator and its performance analysis. *Sol Energy* 2011;85:198–207.
- [8] Lewandowski Allan, Simms David. An assessment of linear Fresnel lens concentrators for thermal applications. *Energy* 1987;12:333–8.
- [9] Singh PL, Ganesan S, Yàdav GC. Performance study of a linear Fresnel concentrating solar device. *Renewable Energy* 1999;18:409–16.
- [10] Sakhrieh A, Ghandoor AAL. Experimental investigation of the performance of five types of solar collectors. *Energy Convers Manage* 2013;65:715–20.
- [11] Koffi PME, Andoh HY, Gbaha P, Toure S, Ados G. Theoretical and experimental study of solar water heater with internal exchange using thermosiphon system. *Energy Convers Manage* 2008;49:2279–90.
- [12] Kumar R, Rosen MA. Thermal performance of integrated collector storage solar water heater with corrugated absorber surface. *Appl Therm Eng* 2010;30: 1764–8.
- [13] Zhai H, Dai YJ, Wu JY, Wang RZ, Zhang LY. Experimental investigation and analysis on a concentrating solar collector using linear Fresnel lens. *Energy Convers Manage* 2010;51:48–55.
- [14] Kostić Ljiljana T, Pavlovic Zoran T. Optimal position of flat plate reflectors of solar thermal collector. *Energy Buildings* 2012;45:161–8.
- [15] Tao YB, He YL, Cui FQ, Lin CH. Numerical study on coupling phase change heat transfer performance of solar dish collector. *Sol Energy* 2013;90:84–93.
- [16] Osório Tiago, Carvalho Maria João. Testing of solar thermal collectors under transient conditions. *Energy Procedia* 2012;30:1344–53.
- [17] Razika Ihaddadene, Nabila Ihaddadene, Madani Bey, Zohra Hamdibacha Fatima. The effects of volumetric flow rate and inclination angle on the performance of a solar thermal collector. *Energy Convers Manage* 2014;78: 931–7.
- [18] Kumar Rakesh, Rosen Marc A. Thermal performance of integrated collector storage solar water heater with corrugated absorber surface. *Appl Therm Eng* 2010;30:1764–8.
- [19] Huang Weidong, Huang Farong, Hub Peng, Chen Zeshao. Prediction and optimization of the performance of parabolic solar dish concentrator with sphere receiver using analytical function. *Renewable Energy* 2013;53:18–26.
- [20] Li Lifang, Dubowsky Steven. A new design approach for solar concentrating parabolic dish based on optimized flexible petals. *Mech Mach Theory* 2011;46: 1536–48.
- [21] Hazami Majdi, Kooli Sami, Naili Nabiha, Farhat Abdelhamid. Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). *Sol Energy* 2013;94(283):298.
- [22] Smith PD. Solar collector with conical element. US Patent; 1977.
- [23] Togrul Inci Turk, Pehlivan Dursun, Akosman Cevdet. Development and testing of a solar air-heater with conical concentrator. *Renewable Energy* 2004;29: 263–75.
- [24] Togrul Inci Turk, Pehlivan Dursun. The performance of a solar air heater with conical concentrator under forced convection. *Int J Therm Sci* 2003;42:571–81.
- [25] Togrul Inci Turk, Pehlivan Dursun. Effect of packing in the airflow passage on the performance of a solar air-heater with conical concentrator. *Appl Therm Eng* 2005;25:1349–62.
- [26] Eskin N. Transient performance analysis of cylindrical parabolic concentrating collectors and comparison with experimental. *Energy Convers Manage* 1999;40:175–91.
- [27] Incropera Frank P, Dewitt DP, Bergman TL, Lavine AS. Principles of heat and mass transfer. 7th ed. Singapore: Wiley & Sons; 2013.
- [28] Hsieh Jui Sheng. Solar energy engineering. Englewood Cliffs, New Jersey: Prentice-hall, Inc.; 1986.
- [29] Hazami Majdi, Kooli S, Lazâar M, Farhat A, Belghith A. Energetic and exergetic performances of an economical and available integrated solar storage collector based on concrete matrix. *Energy Convers Manage* 2010;51:1210–8.
- [30] Attar I, Naili N, Khalifa N, Hazami M, Farhat A. Parametric and numerical study of a solar system for heating a greenhouse equipped with a buried exchanger. *Energy Convers Manage* 2013;70:163–73.
- [31] Duffie JA, Beckman WA. Solar engineering of thermal processes. 2nd ed. New York: Wiley; 1991.
- [32] Methods of testing to determine the thermal performance of solar collectors. ASHRAE standard; 1977. p. 77–93.
- [33] Gang Pei, Guiqiang Li, Xi Zhou, Jie Ji, Yuehong Su. Comparative experimental analysis of the thermal performance of evacuated tube solar water heater systems with and without a mini-compound parabolic concentrating (CPC) reflector($C < 1$). *Energies* 2012;5:911–24.
- [34] Hou HJ. Research on dynamic thermal performance test method of solar collectors. Shanghai Jiao Tong University PhD paper; 2005. p. 92.